Advanced Noise Abatement Procedures for a Supersonic Business Jet

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ABSTRACT

Supersonic civil aircraft present a unique noise certification challenge. High specific thrust required for supersonic cruise results in high engine exhaust velocity and high levels of jet noise during takeoff. Aerodynamics of thin, low-aspect-ratio wings equipped with relatively simple flap systems deepen the challenge. Advanced noise abatement procedures have been proposed for supersonic aircraft. These procedures promise to reduce airport noise, but they may require departures from normal reference procedures defined in noise regulations. The subject of this report is a takeoff performance and noise assessment of a notional supersonic business jet. Analytical models of an airframe and a supersonic engine derived from a contemporary subsonic turbofan core are developed. These models are used to predict takeoff trajectories and noise. Results indicate advanced noise abatement takeoff procedures are helpful in reducing noise along lateral sidelines.

Keywords: Noise; Aircraft performance; Supersonic transports

1.0 INTRODUCTION

Noise standards and recommended practices for new supersonic civil airplanes do not currently exist. Until new regulations are developed, the brief text relevant to supersonic airplanes in Chapter 12 of [1] states that noise limits given for subsonic airplanes may be used, provisionally, as a guideline. For evaluation purposes, we use subsonic certification procedures to predict noise levels in this paper. This is due to the *anticipation* of the authors – given the guidance in Chapter 12 – that new supersonic jet aircraft will be required to certify under subsonic aircraft regulations.

Applicants seeking a noise type certificate for new subsonic jet and large subsonic transport category airplanes are subject currently to the regulations of Chapters 4 and 14 of [1]. The newest noise limits described in Chapter 14 are implemented in phases. While large airplanes (having maximum gross weights over 121klb) are required to meet Chapter 14 limits if the application is received after 2017, smaller airplanes are eligible to certify under older, less demanding noise limits defined by Chapter 4 until 31 December 2020. Further, in the United States and in other countries, flight certification tests may be delayed five additional years after the application date. Thus, an opportunity exists for a transport in the smaller business class – weighing less than 121klb – to certify under Chapter 4 noise limits but not begin noise certification tests until 2025. This report documents the study of a notional Mach 1.4 supersonic business jet in this category.

The requirement of supersonic flight leads to significant differences in configuration, aerodynamics and propulsion relative to a subsonic airplane. A supersonic business jet is likely to have a thin wing with a low aspect ratio and a simple flap system. It is likely to require high takeoff speed before sufficient lift is generated to lift off, and airspeeds higher still to climb with significant thrust margin. But normal noise reference procedures require applicants to climb at airspeeds no greater than 20 knots over than the takeoff safety speed (this is the “not greater than V_2 plus 20 knots” requirement defined by 3.6.2(d)(1) of [1]). It is possible the applicant may want to apply for a departure from this reference procedure to ensure adequate climb performance. Provisions for departures from normal procedures are explained in 3.6.1.4 of [1]. A departure from normal procedures is allowed if the applicant can show the airplane performance characteristics demand it, and if the certificating authority approves it.

Another possible departure from normal procedures involves engine takeoff power settings. Experience in aircraft sizing analyses suggests that supersonic airplanes are likely to be constrained by a takeoff field length requirement. Therefore high engine power settings are required during the ground roll and climbout phases of takeoff. But engines capable of supersonic cruise tend to have high specific thrust, high exhaust velocity, and high levels of jet noise, making noise certification a challenging prospect. Reducing jet noise at the lateral measurement condition, where engine power is maximum, is particularly challenging (A sketch showing the arrangement of the noise measurement monitors is shown in Figure 1.). Researchers during NASA’s Supersonic Cruise Research Program [2] proposed a noise abatement procedure to address noise at the lateral condition. This procedure since has become known as the auto-throttle, or programmed thrust lapse takeoff [3].

As typically envisioned, an advanced takeoff using a programmed thrust lapse begins ordinarily, with maximum thrust applied from brake release through rotation and liftoff. Propulsion noise is highest at maximum thrust, but for observers located laterally across from the airplane, noise is very efficiently attenuated by ground effects. Lateral attenuation is caused by ground surface absorption, by refraction and scattering effects of the air, and by engine-airframe installation effects. At low elevation angles, these effects can attenuate sound along the lateral sideline by as much as 10dB [4]. The programmed thrust lapse procedure exploits lateral attenuation.

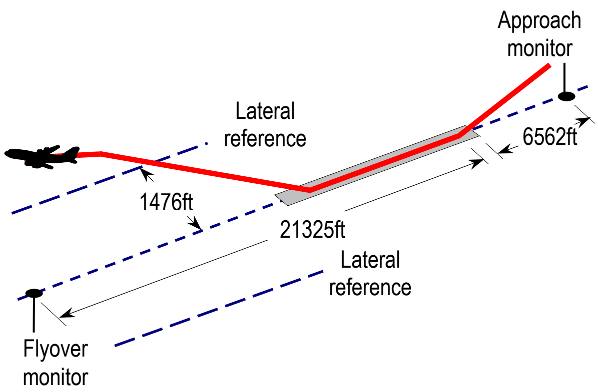

Figure 1. Noise certification monitor arrangement relative to takeoff and landing flight paths.

Immediately after the 35-foot runway obstacle is cleared (but well before the conventional, pilot-initiated noise abatement throttle cutback takes place), engine thrust is automatically lowered to reduce lateral sideline noise. The programmed thrust lapse is more gradual than the rather abrupt pilot-initiated noise abatement throttle cutback occurring later. Ideally, the throttle is reduced as the benefit of lateral attenuation vanishes with increasing altitude. It would likely be implemented over the time required for gear retraction and be completed before the second segment climb begins.

Thus, capitalizing on lateral attenuation via a thrust lapse procedure is a clever idea. Lateral noise is abated, but because takeoff thrust is at maximum through obstacle clearance, takeoff field length does not increase.

However, thrust lapse procedures at low altitude may not be allowed under current regulations. Changes to engine power are not permitted by Section 3.6.2(a) of [1]. This regulation defines minimum safe altitudes (689 to 984 feet, depending on the number of engines), below which engine power setting must remain at maximum. Without permission to operate otherwise, regulations rule out part-power takeoffs for noise certification and would seem to disallow thrust lapse procedures at low altitude. And regulating authorities might be reluctant to approve a pilot-initiated procedure that would increase the workload of the flight crew during takeoff and reduce the rate of climb.

Still, it is thought that a departure from normal reference procedures could be permitted if computer-controlled automatic throttle scheduling is used, making pilot initiation unnecessary. An automatic digital engine control implementation of a programmed thrust lapse could use an airplane’s weight-on-wheels sensors, airspeed, altimeter, attitude and air temperature indicators, and perhaps airport navigational aids to begin preprogrammed thrust reduction.

Afterburning during takeoff to shorten field length was used by the Concorde and has been proposed for some future supersonic transports (e.g., [5, 6]). However, unlike the Concorde, use of afterburners would need to be restricted to just the ground roll due to noise concerns. Even so, lateral ground attenuation may be insufficient to abate noise generated on the runway unless the degree of reheat is limited. A programmed thrust lapse would need to consist of a “wet-to-dry” conversion as landing gear is retracted. This would require the nozzle throat to close just after liftoff. No takeoff afterburning is considered in this study.

Along with an accelerating climbout, a programmed thrust lapse likewise may require approval for a departure from normal takeoff reference procedures defined for subsonic airplanes. This paper documents the initial development of a nonproprietary, public-domain analytical NASA model of a supersonic business jet upon which studies can be performed. Our intent is to use the model to study takeoff procedures and their influence on noise. The accelerating climbout and programmed thrust lapse procedure and their apparent necessity for supersonic transports are the focus of this study.

2.0 ANALYSIS AND DISCUSSION

2.1 Engine Analysis

It is unlikely a completely new engine could be developed and ready in time for 2025 flight tests. Instead, it is more likely the low-pressure spool of a contemporary off-the-shelf engine would be redesigned, resulting in a supersonic variant of an existing subsonic turbofan. In this study, an analytical model of a subsonic CFM56-7B is used as the "donor" engine from which the supersonic engine is derived. Interestingly, the original CFM56-2, granted certification in 1979, was itself derived from the GE F101 and 102 used for the supersonic B-1A bomber. So redesigning the low-pressure spool of a CFM56 once again for a supersonic application would bring the engine family full circle.

Because much engine design data are closely-held, proprietary and unavailable, any analytic simulation of a CFM56 (outside of CFM International) will necessarily have some inherent inaccuracy. Nevertheless, if data can be obtained from public-domain sources (such as type certificate data sheets, manufacturer-provided operating documents, technical reports and manufacturer's websites), simulations of turbofans developed outside of engine companies can be reasonably accurate. The model of the subsonic CFM56 is created with such information using the Numerical Propulsion System Simulation code (NPSS, [7, 8]) to predict engine performance. NPSS is an engine cycle analysis tool developed jointly by NASA and United States aerospace industry. It is currently the accepted, state-of-the-art software for airbreathing engine cycle performance analysis for United States industry, academia, and NASA. The CFM56 model is adapted from work performed under the FAA's Environmental Design Space initiative [9].

The low-pressure spool of the CFM56-7B is redesigned for a Mach 1.4 cruise application. The booster is discarded (with it, supersonic ram effects would elevate aft stages of the compressor to excessive temperature), and the fan and low-pressure turbine are redesigned for a higher pressure ratio. Fan performance is modeled using data collected at NASA from the GE57 scale model fan [10]. The GE57 fan is considered to be perhaps representative of what might be used by an engine manufacturer in a supersonic refan application. It consists of a single stage, has no inlet guide vanes, and operates at peak efficiency at a pressure ratio of 2.2. Fan pressure ratio is a design variable strongly influencing engine performance. A high fan pressure ratio is preferred to create exhaust velocity high enough for supersonic flight, while a low fan pressure ratio is required to meet takeoff and landing noise requirements. Fan pressure ratio, along with a practical extraction ratio, directly determines the bypass ratio of the engine. This poses conflicting requirements for supersonic engine designers. In this study, an initial mixed-flow engine cycle was studied using unscaled GE57 fan performance data. This led to supercritical nozzle pressure ratios at low altitude and high levels of jet shock cell noise during takeoff. That engine design was deemed untenable and discarded. The current engine cycle in this study uses the GE57 fan data, but with pressure ratios scaled low enough that the nozzle is on the cusp of choke near sea level. With a small amount of engine derating at low altitude and a programmed thrust lapse, jet shock cell noise is eliminated after liftoff.

Another key design choice is whether to forcibly mix the core and bypass streams or to allow them to remain separate. There are compelling reasons to mix the streams. There is usually an increase in gross thrust when flows are forcibly mixed and exhausted through a common nozzle, with the benefit increasing with increasing core stream temperature. Although the benefit is slight, it can be important to net thrust at high speed when ram drag is high. And the outer mold lines of a single-stream nozzle are preferred over those of a more complex coannular nozzle if sonic boom reduction is important. In this study, core and bypass streams are forcibly mixed through a lobed mixer. The design extraction ratio is kept near unity so that mixer bypass port and mixer exit Mach numbers are always less than 0.5.

The mixed flow exits through a single-stream convergent-divergent plug nozzle. The centerbody plug and nozzle throat are fixed while the divergent flaps are variable. The plug is important in keeping aftbody boattail angles small during supersonic cruise while also lowering jet noise slightly. At low altitudes, the divergent nozzle flaps are closed to

a minimum area so that the nozzle exit plane is the throat. Solid models of the CFM56-7B and the derived supersonic turbofan are shown in Figure 2. Not shown in the Figure is the external compression inlet for the supersonic engine.

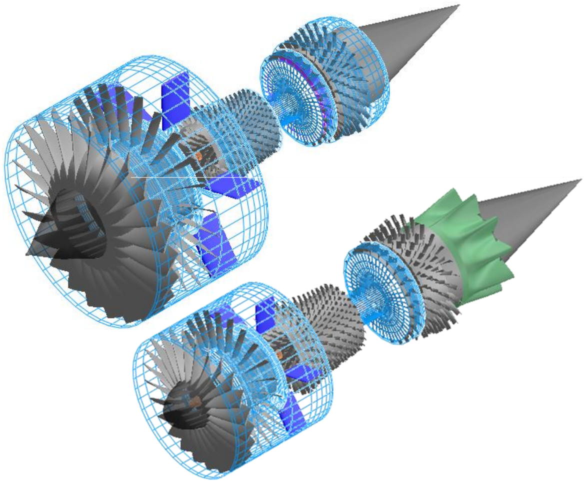

Figure 2. Solid models of the CFM56-7B (top) and notional modified supersonic variant (bottom).

At the cycle design point, the compressor and the high-pressure turbine are held in off-design mode. NPSS performance map scalars of the compressor and high-pressure turbine from the CFM56 donor engine are manually specified. This keeps the core of the supersonic derivative engine identical to the CFM56 core. Bleed flow fractions and core flow passage areas are also held constant. Hot section temperatures are kept nearly as high as the CFM56 maximum takeoff temperatures. But since the supersonic variant would spend several hours at maximum temperature (compared to just a few minutes during takeoff for a subsonic turbofan), this becomes a rather important assumption. Maintaining high temperatures is justified by assuming increased hot section overhaul frequency (not uncommon for a business jet application), new turbine airfoils with improved materials and coatings, and better cooling effectiveness. A summary of engine performance data is shown in Table 1. Ambient conditions above 10,000 feet use International Standard Atmosphere (ISA) conditions, while conditions nearer sea level use standard hot day (ISA+27°F) conditions. Performance data at sea level are shown after engine derating.

And although not studied, a separate flow turbofan may be an interesting alternative engine design. The bypass stream of a coannular nozzle provides an effective means to reduce the shear velocity of a supersonic core jet. This reduces Mach wave radiation that can be the principal noise source of a supersonic jet. A separate flow turbofan could be an engine architecture that allows fan pressure ratio to be higher while still keeping jet noise at acceptable levels

Table 1
Supersonic derivative engine performance summary.

	M1.4, 50kft, ISA	**M0.25, sea level, ISA+27°F**	**Sea level static, ISA+27°F**
Net thrust, lb	3330	14,140	16,620
Specific fuel consumption, lb/hr/lb	0.943	0.588	0.479
Bypass ratio	2.9	2.9	3.0
Burner temperature, °R	3300	3150	3130
Turbine inlet temperature, °R	3180	3040	3020
Compressor exit temperature, °R	1450	1440	1430
Overall pressure ratio	22	21	21
Fan pressure ratio	2.0	1.9	1.9
Compressor pressure ratio	11.2	11.1	11.2
Extraction ratio	1.1	1.1	1.1
Nozzle pressure ratio	5.9	1.9	1.8

2.1.1 Airframe Analysis

Most properly, an aircraft conceptual design should begin with a study to determine basic vehicle performance, payload and mission requirements. Concurrently, an experienced airplane designer would loft a vehicle and define its geometry well enough to predict its aerodynamics and weight. A performance constraint and sizing analysis would determine optimum vehicle characteristics to perform the desired mission. Airframe and propulsion analysts would team together and iterate the process until closure. Due to time and resource constraints, however, this usual practice is replaced with a simpler approach. The scope of this study is to assess advanced takeoff procedures and their impact on noise, and so the focus is on propulsion design, takeoff performance and noise predictions. Insight can be gathered with reasonable assumptions for airframe performance. In subsequent phases of this study, more complete vehicle analysis will be made.

A supersonic business jet with a maximum gross weight of 121klb is selected for this study for reasons discussed in the introduction. Engines are designed for a Mach 1.4 cruise at 50,000 feet. Three engines are necessary to provide sufficient thrust for cruising if the vehicle's lift-to-drag ratio is approximately 10. The engines are assumed to be mounted on top of the wing and fuselage to shield forward-radiating fan noise from observers on the ground during takeoff and approach. The nozzle exit planes extend aft of all airframe surfaces; thus fan exit noise, core noise, and jet noise – a distributed noise source in any case – do not benefit from wing shielding. A solid model of the vehicle concept is shown in Figure 3.

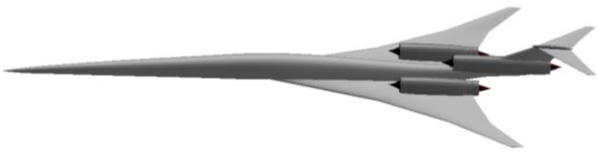

Figure 3. Solid model of notional supersonic business trijet.

Low-speed aerodynamics are required to compute takeoff and approach trajectories necessary for a certification noise analysis. Aerodynamics in the form of scalable lift and drag coefficients are taken from a Boeing study of a Mach 1.6, 180klb supersonic transport [11]. Lift and drag coefficients as functions of angle of attack are given for three flap settings. It is assumed that if the wing planform and high lift devices of the Boeing vehicle and our reference vehicle are similar, then the low-speed aerodynamics may also be similar. A wing reference area corresponding to a takeoff wing loading of 90 pounds per square foot is assumed in order to compute actual aerodynamic forces for a trajectory analysis. In later phases of this study, the actual wing loading will result from an airplane sizing analysis.

2.1.2 Takeoff Analysis

Takeoff and climb at high speed may be preferred for many supersonic aircraft. This preference can be shown for the supersonic business jet in this study by constructing its thrust demand curves. These are shown in Figure 4 for level and steady flight at maximum weight using takeoff flaps at an altitude of 2000 feet. Unlike a medium subsonic commercial airplane of similar weight in these conditions, which may have a minimum drag speed of perhaps 200 knots, our supersonic business jet's minimum drag speed is predicted to be nearly 300 knots. Speeds below the minimum drag speed are in the so-called region of reversed command, where to fly more slowly requires more thrust to overcome increasing lift-dependent drag. Flying safely in this region requires adequate thrust margins. If climbout speeds are limited by 3.6.2(d)(1) of [1], very high rotation and liftoff speeds would seem to be in order, so that the climbout would take place at as high a speed as possible. Since modern aircraft tires are rated to approximately 200 knots, rotation speed in this study is assumed to occur at 190 knots. This results in a liftoff speed of 196 knots and a takeoff safety speed of 202 knots.

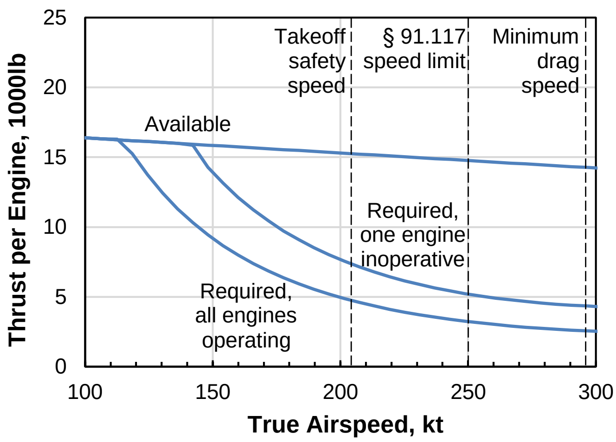

Figure 4. Thrust demand of supersonic business jet for level steady flight at 2000 feet.

Even so, 202 knots is still well inside the region of reversed command. This demonstrates the need for high-speed ground rolls (delayed rotations) and quite possibly an accelerating climbout. Seemingly, an excellent case could be made to permit a departure from the climbout speed limit requirement defined by 3.6.2(d)(1) of [1].

In addition, unless permission is granted otherwise, flight in excess of 250 knots under 10,000 feet is prohibited in the United States (and in many other countries) by the Code of Federal Regulations 14 CFR § 91.117(a). Accelerating climbouts are studied in this report, but they are limited to speeds under 250 knots.

2.1.2.1 Standard Takeoff Procedures

A takeoff field length calculation in accordance with 14 CFR § 25 is made for this airplane using NASA's Flight Optimization System, FLOPS [12]. It is assumed to rotate at an angle of attack of 13 degrees. Maximum usable lift coefficient is assumed to be 1.0. For the critical outboard engine failure calculation, engine-out yaw drag is estimated using handbook methods. Balanced field length is calculated to be 7550 feet; however the takeoff field length is, instead, determined by 115 percent of the all engines operating field: 7670 feet. In either event, field lengths of this distance should be satisfactory for this class of airplane, giving credibility to the takeoff wing loading assumed earlier. The minimum second segment climb gradient of 2.7 percent required for trijets with one engine inoperative is satisfied.

Next, a takeoff calculation for noise certification from a sea level field on a standard acoustic day is made in accordance with the requirements in 3.6.2 of [1]. No climbout acceleration or programmed thrust lapse is performed. Above the minimum safe altitude, engine power is reduced during a pilot-initiated cutback such that the climb gradient is zero with one engine inoperative, or four percent with all engines operating. The engine power cutback is designed to reduce noise at the flyover monitor. Many certification applicants vary the time and position of the cutback (using an equivalent procedure) to minimize noise slightly at this location. In this study, however, the cutback is complete 17,000 feet from brake release, and the flyover noise is determined entirely by the cutback power noise signature. This takeoff is depicted by the solid lines in the plots for steady, non-accelerating climbouts in Figure 5. This standard takeoff is permissible without departures from normal procedures defined by 3.6.2 of [1].

2.1.2.2 Advanced Takeoff Procedures

Noise certification takeoffs using programmed thrust lapse rates of 5 and 10 percent are shown in Figure 5. Thrust is automatically reduced by digital engine controllers beginning at the runway obstacle and is completed by the start of the second segment climb.

Automatic control of engine thrust has been implemented on several popular civil aircraft, albeit not for noise reduction purposes. Regulations governing automatic takeoff thrust control systems were defined under 14 CFR § 25.904 in 1987.

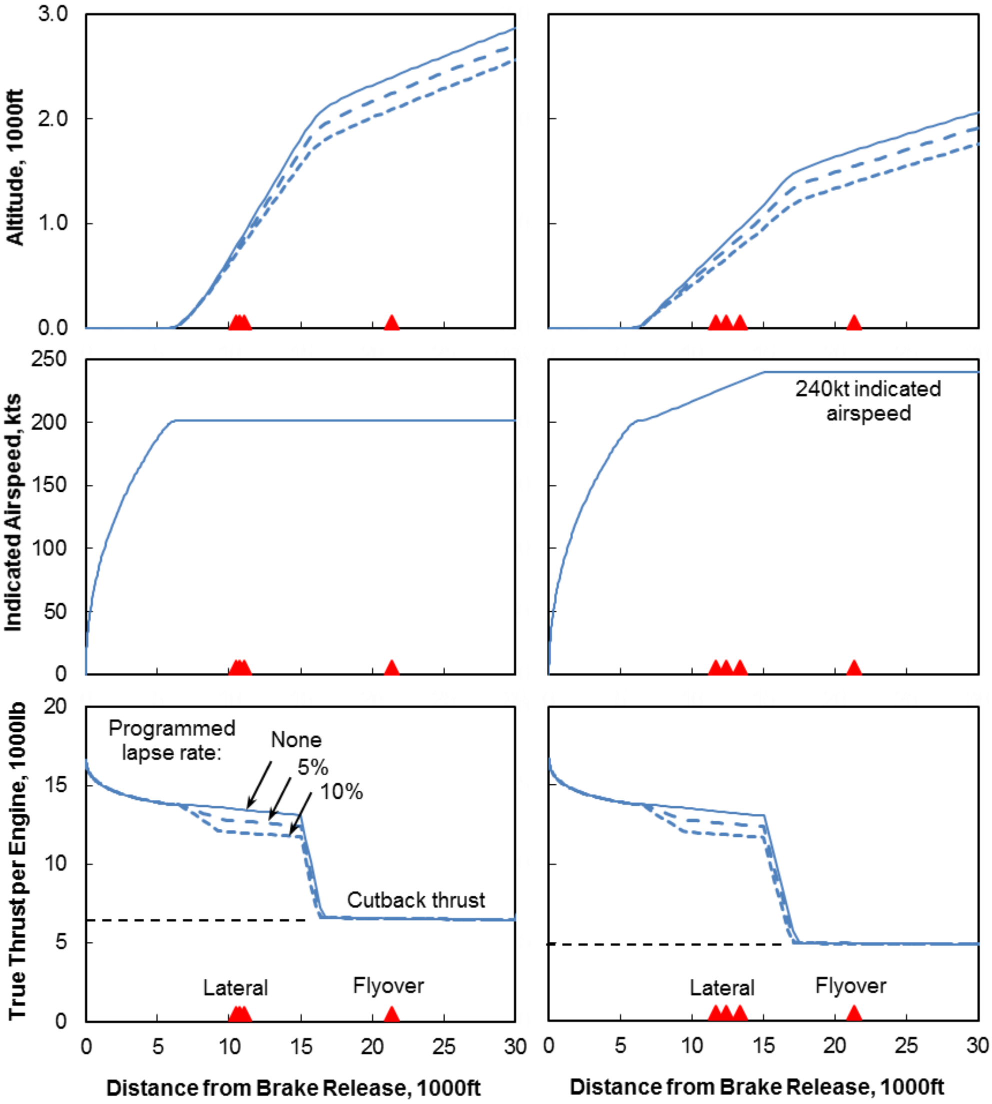

Figure 5. Takeoff trajectories with steady climbout (left) and accelerating climbout (right), showing influence of programmed thrust lapse rate and noise abatement cutback.

The notion of using programmed thrust lapse as an automatic noise abatement mechanism might be designed as a variable noise reduction system (VNRS) under [13]. Infrequently implemented, a VNRS is a system where noise is abated automatically without flight crew intervention.

Alternately, an examination of the FAA special conditions docket for airplanes having automatic thrust control systems at low altitude is revealing. Digital engine controllers on the Airbus A320 family have an “autothrust” feature that automatically increase thrust with no change in power lever position in the event of a stall [14]. Also, a special condition [15] has been granted to the Embraer 170/190 family in the event of engine failure, allowing a digital engine controller to automatically increase thrust on the operative engine during a go-around. These examples suggest digitally-automated thrust control procedures such as programmed thrust lapse might be implemented for supersonic aircraft on a case-by-case basis using a special conditions exception. In any event, greater clarity may be helpful if automated thrust control is an enabling noise abatement requirement for supersonic transports.

Satisfying minimum climb gradient requirements may be an important consideration when using a programmed thrust lapse. In the event of an engine failure during climbout, 14 CFR § 25.121 specifies a minimum climb gradient requirement in the segment defined

between the points when gear is retracted and an altitude of 400 feet. This regulation requires the remaining operative engines to be at “the power or thrust available when retraction of the landing gear is begun.” This, by our assumptions, is the maximum takeoff thrust prior to the programmed thrust lapse. Thus an automatic takeoff thrust control system would be needed to increase thrust on the remaining engines. Further, time to spool the engines up to maximum power must be considered, and so the amount of programmed thrust lapse could be limited.

Noise certification takeoffs using accelerating climbouts are also shown in Figure 5. There is some flexibility in how an acceleration segment may be performed. Both altitude gain and acceleration in some proportion are possible. In this study, arbitrarily but with some logic, the airplane simultaneously climbs and accelerates such that an indicated airspeed of 240 knots is reached at the beginning of the pilot-initiated throttle cutback. This airspeed is slightly less than the maximum 250 knot limit in the United States and elsewhere. As noted earlier, a high-speed climbout would require a departure from 3.6.2(d)(1) of [1], with the justification that it is required to ensure adequate thrust margin and climb performance. In operational practice, high-speed climbouts are sometimes allowed. Permission may be granted on a case-by-case basis if other aircraft are not in the vicinity. In the future, nearby aircraft may need to give more room to supersonic transports. This practice is already common today, where greater spacing intervals are given to large aircraft due to their wake turbulence.

2.1.2.3 Influence on Noise

Advanced takeoff procedures have several positive impacts on noise, in addition to reducing lateral noise as noted already. A high-speed climbout results in less shear between the jet and ambient air, resulting in weaker turbulence and less jet noise. A high-speed climbout also results in generally lower noise due to shorter event duration. And higher airspeed also creates more lift, allowing a deeper pilot-initiated engine thrust cutback. This last effect is noticeable in Figure 5. However, either a programmed thrust lapse or an accelerating climbout results in lower climb rates and much lower altitudes over the flyover monitor. The consequence of this is that a programmed thrust lapse tends to lower lateral noise at the expense of flyover noise.

2.1.3 Noise Analysis

It is helpful to begin a noise assessment of a conceptual airplane by considering how loud it can be. Maximum Effective Perceived Noise Levels (EPNLs) for a 121klb trijet are presented in Table 2 given the language in Annex 16. Maximum lateral, flyover, and approach levels for Chapter 3 are shown. Since supersonic transports are expected to be loudest just after takeoff, lateral EPNLs for Chapter 4 and for Chapter 14 are set to the maximum levels permitted. The remaining requirements are split evenly between flyover and approach. Margins naturally would be added to these maximum targets to increase confidence before a product launch decision.

Table 2
Maximum target levels required to meet Chapters 3, 4 and 14 for a 121klb trijet, EPNdB.

	Lateral	Flyover	Approach	Cumulative
Chapter 3	95.7	92.8	99.5	287.9
Reduction*	0	-5	-5	-10
Chapter 4	95.7	87.8	94.5	277.9
Reduction*	-1**	-3	-3	-7
Chapter 14	94.7	84.8	91.5	270.9

*Maximum permitted lateral noise; remaining requirement split evenly between flyover and approach.
**Chapter 14 requires a margin of not less than 1 EPNdB below Chapter 3 limits at each point.

Noise certification predictions are made using NASA’s Aircraft Noise Prediction Program (ANOPP, [16, 17]). Engine state data computed by NPSS are fed into ANOPP as functions of flight speed, altitude and engine power setting. Jet noise, fan noise, fan treatment suppression, core noise and several airframe sources are predicted using the

methods of Stone [18], General Electric [19, 20], Emmerling [21] and Fink [22], respectively, using best practices.

These noise sources are analytically flown along the trajectories described in the previous section and propagated to noise certification monitors on the ground. The source levels are computed at half-second intervals using engine state data at the correct flight condition and engine power. This is particularly important in modeling noise during the programmed thrust lapse procedure. Noise propagation effects include spherical spreading, Doppler shift and convective amplification, atmospheric absorption, ground reflections based on data for grass-covered ground, and lateral ground attenuation.

With engines mounted above the vehicle, noise shielding effects must be considered. Shielding (also referred to as barrier attenuation or insertion loss) is an acoustic diffraction phenomenon where sound waves are attenuated when propagated past an impermeable barrier placed between the noise source and an observer. In this study, a simple empirical diffraction model based on optical diffraction theory is used. The model was originally proposed by Maekawa [23] and is reproduced in many foundational acoustic textbooks. Shielding is particularly efficient when the observer is located in the “shadow region” where the noise source is obscured. The delta wing (see Figure 3) provides excellent shielding of forward-radiated fan inlet noise. All other sources are not shielded. Jet noise is a distributed source generated downstream throughout the axial exhaust plume. Core noise is predominantly aft-radiating and is assumed to radiate through the exhaust. Fan exit noise also escapes through the nozzle but it is attenuated by treatment in the bypass duct.

Certification noise predictions are shown in Table 3 and are compared to published noise type certificate data of subsonic aircraft in Figure 6. Predictions are made for steady and accelerating climbouts and with programmed thrust lapse rates of 5 and 10 percent. Plotted in Figure 6 are published data of over 11,000 Chapter 4 aircraft types. The standard takeoff (solid red symbol) uses no advanced takeoff procedures and satisfies the requirements of Annex 16 without departures from 3.6.2. The advanced takeoff (open red symbol) uses a 10 percent programmed thrust lapse rate and an accelerating climbout.

Table 3
Certification noise predictions, EPNdB.

	Steady			**Accelerating**		
Climbout lapse rate, %	0	5	10	0	5	10
Lateral	**97.1**	**96.0**	**94.8**	**95.8**	**94.5**	**93.3**
Flyover	84.3	84.9	85.4	82.3	83.1	84.0
Approach	95.7	95.7	95.7	95.7	95.7	95.7
Cumulative margins:						
Chapter 3	10.8	11.4	12.0	14.1	14.6	15.0
Chapter 4	0.8	1.4	2.0	4.1	4.6	5.0
Chapter 14	-6.2	-5.6	-5.0	-2.9	-2.4	-2.0
Chapter qualification	3*	3*	4	3*	4	4

* “Trading” is necessary to meet Chapter 3 limits.

Lateral EPNL is primarily a function of jet noise, without significant influence from vehicle performance. Lateral noise tends to peak wherever the airplane reaches an altitude of about 1000 feet, where ground attenuation effects vanish but before the airplane gains more altitude. Thus vehicle aerodynamics play only a small role in lateral noise level.

Approach and flyover EPNLs, however, are strongly influenced by vehicle aerodynamics and performance. Approach noise levels tend to increase if high-lift wing devices do not improve lift adequately. In this study, it was necessary to add drag to the approach aerodynamics of [11] (perhaps in the form of speed brakes) to limit approach speed to 160 knots. The simple addition of drag devices to keep approach speed acceptable is undesirable since thrust must increase to overcome drag while holding the three degree glide slope required by 3.6.3(a) of [1]. It is far better, instead, to improve lift or approach noise will increase. But thin supersonic wings may not be able to accommodate efficient,

more complex high-lift devices. Even so, approach noise is predicted to be similar to published data for airplanes in this weight class.

During takeoff, the engine power setting for the noise abatement cutback is determined by climb rate, which in turn is also a strong function of vehicle aerodynamics. Although it may appear from these results that flyover margin is sufficient, that margin could erode quickly if levels are underpredicted.

Thus, the approach and flyover EPNLs in this assessment likely have the most uncertainty due to the lack of rigor in our analysis of high lift devices and our assumptions of engine placement and wing shielding. Lateral noise predictions, therefore, are emphasized. Fortunately, advanced takeoff procedures and their influence on lateral noise are the focus of this study. A sensitivity study to system uncertainties is planned in a later phase of this work.

Lateral EPNLs have the narrowest predicted noise margins. Indeed, the lateral EPNL for the standard takeoff is not predicted to qualify for Chapter 4. It does, however, qualify for Chapter 3 (despite exceeding the Chapter 3 lateral limit) by virtue of "trading," a practice once allowed under Chapter 3 certification. Trading allowed applicants to exchange an exceedance at one or two points if the exceedance(s) were offset by a corresponding lower amount at another point or points.

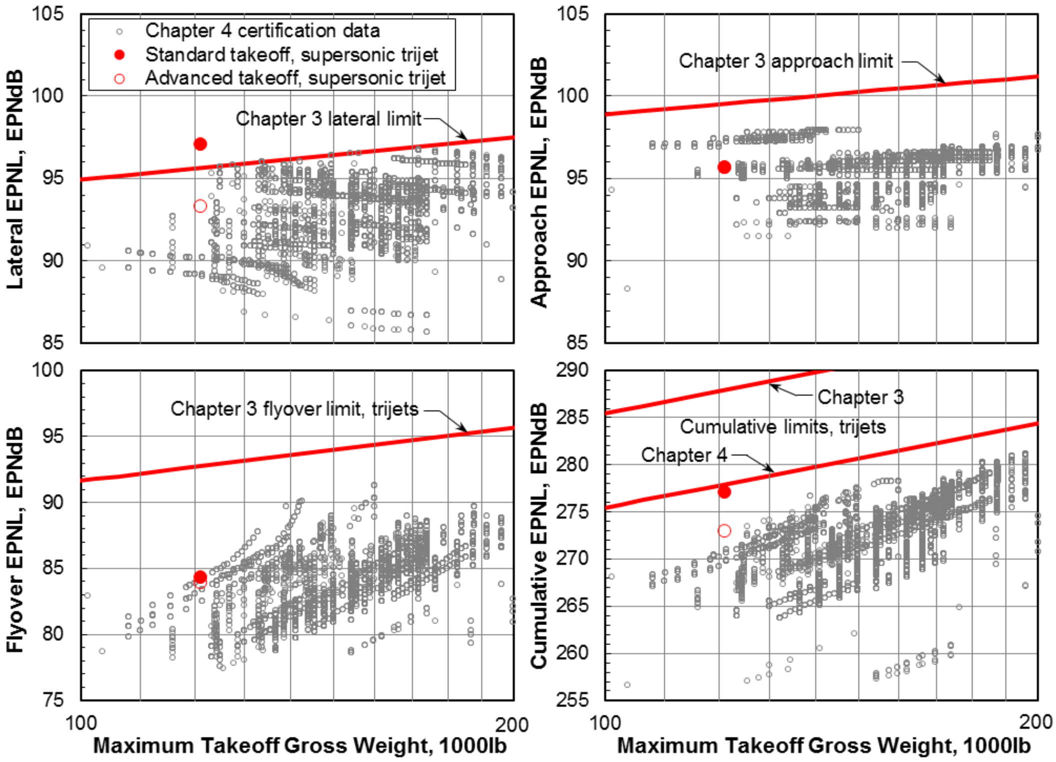

Figure 6. EPNL predictions compared to Chapter 4 data, showing influence of advanced takeoff procedures.

2.1.4 Implications of Advanced Takeoff Procedures

Noise at the lateral condition can be perhaps made acceptable for Chapter 4 certification with a programmed thrust lapse or with a thrust lapse combined with an accelerating climbout, albeit with narrow lateral margins. Other source noise reduction technologies mature enough for a near-term supersonic transport could also be used to improve margin. But using a programmed thrust lapse to reduce lateral noise is not without consequences. Lowering thrust adversely affects the aircraft's ability to climb and forces the aircraft to pass over the flyover noise measurement point at a lower altitude than if a standard takeoff had been performed. For this reason, the programmed thrust lapse procedure, despite its

lateral noise reduction advantage, is in conflict with keeping flyover noise levels low. This can be seen from the noise footprints plotted in Figure 7.

The benefit of an accelerating climbout is clear. It is helpful in ensuring adequate climbout thrust margin for supersonic transports, and it has the positive side effect of reducing noise. But given the trade between lateral and flyover noise when a programmed thrust lapse is used, a fair question to ask is whether it should be implemented at all. In most instances, more people live downrange of airports than alongside airport runways. The programmed thrust lapse procedure is likely to subject more people to noise. It also sacrifices altitude or airspeed (or both, depending on how the climbout is conducted), at a time when they are most welcome. And developing simplifying equivalent procedures for noise certification flight tests seems difficult. The concept exploits the interaction between lateral attenuation – vanishing with increasing altitude – and a noise abatement thrust reduction. Mimicking the behavior of the takeoff while accurately representing the complex acoustics of the problem may be challenging.

Yet the issue of satisfying the maximum lateral noise level merits further discussion. One possibility is to simply relax the maximum lateral limit for future supersonic airplanes. Another possibility might be to revive the practice of trading. Since there appears to be margin at the other two conditions (at least in this study), supersonic airplanes might be permitted to exceed the lateral limit by exchanging margin.

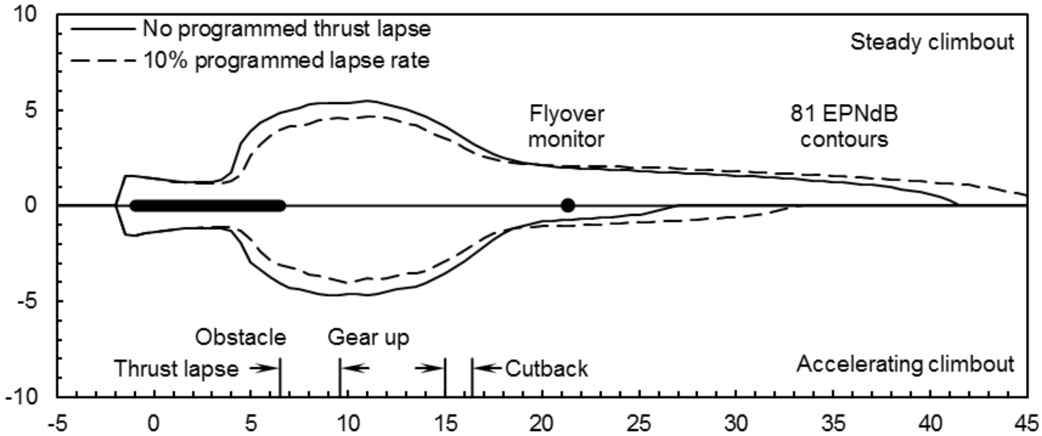

Figure 7. Takeoff EPNL footprints showing influence of programmed thrust lapse: steady climbout (top), accelerating climbout (bottom). Plan dimensions in thousands of feet.

3.0 CONCLUSIONS

Analytical models of a near-term supersonic business jet are developed and used to study advanced takeoff noise abatement procedures. Two advanced procedures – accelerating climbout and programmed thrust lapse – and their apparent necessity for supersonic transports are evaluated in this study. Results show these procedures are helpful in reducing lateral noise but may require departures from normal reference procedures defined by regulations. An accelerating climbout is shown to reduce both lateral and flyover noise, but a programmed thrust lapse is shown to reduce lateral noise at the expense of flyover noise.

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